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THE CALCULATION OF THEORETICAL CHROMOSPHERIC MODELS AND THE INTERPRETATION OF THE SOLAR SPECTRUM

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Final Report

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1. INTRODUCTION

Since the early 1970s we have been developing the extensive computer programs needed to construct models of the solar atmosphere and to calculate detailed spectra for use in the interpretation of solar observations. This research involves two major related efforts: work by Avrett and Loeser on the Pandora computer program for non-LTE modeling of the solar atmosphere including a wide range of physical processes, and work by Kurucz on the detailed synthesis of the solar spectrum based on opacity data for over 58 million atomic and molecular lines. Our goals are 1) to determine models of the various features observed on the Sun (sunspots, different components of quiet and active regions, and flares) by means of physically realistic models, and 2) to calculate detailed spectra at all wavelengths that match observations of those features. These two goals are interrelated: discrepancies between calculated and observed spectra are used to determine improvements in the structure of the models, and in the detailed physical processes used in both the model calculations and the spectrum calculations. The atmospheric models obtained in this way provide not only the depth variation of various atmospheric parameters, but also a description of the internal physical processes that are responsible for non-radiative heating, and for solar activity in general.

A byproduct of our research will be the determination of the solar irradiance spectrum at all wavelengths for any state of solar activity as measured by various disk images. To the degree of accuracy that our calculated spectra agree with solar observations, we should be able to relate the intensity at one wavelength to that at any other wavelength in quiet or active regions anywhere on the solar disk. Thus we can compute needed solar irradiances at unobserved UV or EUV wavelengths based on available disk images in, say, the Ca II K line, the He 1083nm line, or from magnetograms, since irradiance variations are due almost entirely to the extent and location of active regions on the disk. Changes in the concentration of ozone and other molecules in the Earth's upper atmosphere are observed to be correlated with UV and EUV solar irradiance variations on time scales from a few days up to the 27-day period of solar rotation. Direct UV and EUV irradiance measurements during the last two 11-year solar activity cycles have been too few in number and too uncertain in absolute calibration to determine the solar input to long-term changes in the molecular chemistry high in the Earth's atmosphere. The calculated model spectra now may be accurate enough to reconstruct this past record of UV and EUV irradiance.

2. RECENT PROGRESS

We find that we cannot adequately investigate the interaction between the corona and chromosphere using static models. We have spent considerable effort in the past year in deriving the theory and developing the numerical treatment of radiative transfer and statistical equilibrium in flowing gas. The problem of consistently including advection as well as particle diffusion in non-LTE calculations for optically thick media is highly complex and has never been adequately solved before. We are now in the final stages of this development and expect to obtain results soon.

This is a continuation of our research on particle diffusion in collaboration with J.M. Fontenla, who now works for a private company in Boulder. Fontenla, Avrett, and Loeser (1993) showed that particle diffusion, in addition to thermal conduction, can bring down from the corona the energy needed to account for the observed emission from the lower transition region. As a result, the earlier semiempirical transition region models have been replaced by theoretical energy-balance models. These theoretical models with steep gradients produce strong Lyman alpha emission because neutral hydrogen atoms diffuse upward to produce this emission near 40,000K rather than near the 20,000K temperatures in local statistical equilibrium calculations without diffusion. Protons diffusing downward from higher to lower temperatures carry ionization energy to supply the base of the transition region.

We carried out a detailed study of how the He I and He II lines are formed (Fontenla, Avrett, and Loeser, 1993; Avrett, Fontenla, and Loeser, 1994) and did not find any inconsistency between the computed and observed He I 58.4 and 1083 nm lines and 50.4 continuum and He II 30.4 and 164 nm lines and 22.7 continuum. Diffusion in the lower transition region may account for the generally smaller and highly variable helium abundance in the solar wind, but mass outflow and mixing in the transition region are needed to avoid a very small predicted helium abundance in the corona. Diffusion may also explain the observed coronal abundance depletion of elements with high first ionization potential, since elements that are fully ionized in the low transition region would be subject to smaller differential effects of proton and neutral-atom diffusion. We interpret the "FIP effect" as due to trapping and abundance enhancement of high-FIP elements near the base of the transition region in the absence of outflows, and the release of these elements where outflows occur.

In collabortion with Fontenla, O.R. White, and P.A. Fox, we are carrying out spectral irradiance calculations based on a combination of 7 spatial component models of the solar atmosphere:

A Faint regions of network-cell interiors
C Average network-cell regions (average quiet sun)
E Average network lanes
F Bright network lanes
H Average plage areas
P bright plage areas
S Large sunsport unbrae

The distribution of these components on the solar disk at any given time is established from disk images available at a few wavelengths. We can compute the complete spectrum that would be emitted by any component located at any position on the disk. Thus we can compute the corresponding spectral irradiance at any wavelength. We are completing the first of several papers describing these results: "Calculation of Solar Irradiances. I. Synthesis of the Solar Spectrum", to be submitted to the Astrophysical Journal.

Kurucz is still recovering from moving his office. He did not make any new CD-ROMs but continued to distribute the 23 already made. He is setting up a web site that will eventually contain all of his atomic and molecular data, all of the observed spectra, the predicted irradiance, computed spectra, the computer programs for model atmospheres and spectrum synthesis, and other new material that might be useful.

Kurucz made little progress on atomic and molecular data. He expects to get back into full production in 1998. He continued to improve Lyman alpha wing opacity, merging of hydrogen line series into continua, and He I line profiles in his spectrum synthesis program. He has been editing NIST data files to use as input into the atomic calculations. He used the new hyperfine splitting constants for Co I from Pickering (ApJSupp 107,811,1997) to divide up all of the Co line data. The computed profiles in the solar spectrum now look like the real thing.

Kurucz translated his old 1979 Cray non-LTE spectrum synthesis program to his workstation. He is still debugging the partial redistribution section and he is updating the coronal appoximation line data with tables used by Nancy Brickhouse for AXAF.

We now have enough disk space to work on reducing all of Brault's Kitt Peak FTS solar spectra at once. We continue to find new problems with atmospheric transmission. We expect to finish the center of the disk and flux spectra from 0.3 to 5.0 microns and the limb out to 2 microns during 1998. The main problem with reducing these spectra and with the ultraviolet spectra is still missing atomic and molecular data that make it is difficult to distinguish noise or to set wavelength scales.

Kurucz got his opacity sampling model atmosphere program, ATLAS12, working for cool stars. A 30000 frequency model for the sun is not significantly different from our ATLAS9 distribution function model that runs fifty times as fast.

Kurucz continued to investigate convection in model atmospheres and the shortcomings of the mixing length formulations for treating it. There are problems with the solar spectrum that seem to be caused by the presence of hot and cold elements that cannot be averaged away. For example Balmer line profiles give different temperatures than the continuum in the sun. A hot element has much stronger hydrogen lines and much weaker molecule lines than the mean, and a cold element has much weaker hydrogen lines and much stronger molecule lines than the mean.

Another problem that Kurucz has begun to investigate is the effect of depth-dependent microturbulent velocity on the models. The microturbulent velocity in empirical models has a minimum at the temperature minimum and increases inward and outward. The theoretical models have been computed with constant microturbulent velocity. The theoretical models have extra opacity at the temperature minimum and too little at large depths compared to the real sun. Changing the opacity changes both the radiation and the convection. We do not yet have results.

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